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GODDARD CONTRIBUTIONS TO THE 1963 JAIPUR CONFERENCE ON COSMIC RAYS

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MODULATION OF LOW ENERGY GALACTIC COSMIC RAYS

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(read by C. E. Fichtel)

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The exact way in which the cosmic ray energy spectrum changes with solar activity has been of particular interest because the experimental determination of this feature provides one of the most severe tests of any theory related to cosmic ray modulation. The helium and proton components in addition to being the most abundant also have the additional advantage of having charge to mass ratios which differ by a factor to two. Therefore, having a markedly different velocity for a given rigidity, these particles provide a means for separating rigidity and velocity effects.

In order to continue the study of the problem of the variation of the galactic cosmic ray proton and helium nuclei spectra, a series of balloon flights was made from Fort Churchill, Canada by Goddard beginning in 1961. It is the aim of this paper to present the results of the nuclear emulsion studies of the hydrogen and helium nuclei obtained in 1962 and 1963 and compare them to those obtained in 1961[1] and the earlier results of many experimentalists from the period of increasing solar activity.

One method of comparing the period of rising cosmic ray flux with the declining phase is to plot the integral helium nuclei flux above 250 MeV/n as a function of the neutron monitor rate which gives some measure of the higher energy cosmic rays of all charges. Figure 1 shows the smooth curve determined from many points for this period by McDonald and Webber[2]. Also shown on this figure are the points obtained by the Goddard emulsion group

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†On leave of absence from Tata Institute of Fundamental Research.

in 1961, 1962, and 1963. As can be seen, the points agree well with the smooth curve.

A much more detailed and stringent comparison between the two periods is the comparison of the differential energy spectra of the helium nuclei in the present experiment with those obtained for the same neutron monitor rate during the declining phase of cosmic ray flux. Figure 2 shows the spectra for various neutron monitor counting rates during the declining phase of cosmic ray activity as given in Webber's review article[2]. These curves fit both the proton data and the helium nuclei data multiplied by seven. In general, the helium nuclei data extended down to about 1.2 BV/Nucleon and the proton data extended from 0.8 to 1.4 BV. As can be seen, there is reasonable agreement between the helium nuclei data and the curves for the declining cosmic ray phase at the same neutron monitor rates although there is a suspicion that the helium points from this work may fall below the curve at the lowest rigidities where measurements were made. In order to obtain a more quantitative impression of the change in spectral flux from 1961 to 1962, the following numbers can be compared. The integral flux for helium nuclei with energies greater than 250 MeV/nucleon was 206 ± 13 particles/(m^2 sr.sec.) in 1961 and 221 ± 18 particles/(m^2 sr.sec.) in 1962. For the energy interval from 75 to 250 MeV/nucleon the flux was 12.7 ± 1.7 particles/(m^2 sr.sec.) in 1961 and 32.5 ± 4.1 particles/(m^2 sr.sec.) in 1962. Hence, between 1961 and 1962 there was a significant change in the helium particle flux below 250 MeV/nucleon and relatively little above.

Turning now to the protons it is known that there is a substantial secondary proton flux from interactions in the atmosphere above the detector. There is not space to describe the corrections in detail here, but the discussion of the method along with self-consistency arguments has been given in some detail in the earlier paper and will be treated further in the final publication of this work. Allowance has been made for the uncertainty in the interaction correction by drawing appropriately large errors in figure 2. This figure shows that there is a general tendency for the proton flux to increase during the period from 1961 to 1963, and that at least in 1961 and 1962 the proton points lie above a reasonable extension of a smooth curve through the helium nuclei data multiplied by seven.

There is another set of data for which the analysis has just been completed which bears on this problem. Balasubraymanyan and McDonald[a] obtained a differential helium nuclei spectrum during the same period in 1963 as the proton data of this work. It agrees well with curve C above about 1.5 BV, but falls more quickly below this rigidity. These data are shown in figure 3, along with the results of this work in 1963 and 1961. The 1962 results lie in between those of 1961 and 1963, and were not included only to avoid unnecessarily complicating the figure. All these data are seen to be consistent with there being a difference between the proton differential rigidity spectra and the helium one multiplied by seven below about 1.2 BV.

Hence, these combined results suggest strongly that there is a splitting of the proton differential spectrum and the helium nuclei one multiplied by seven below about 1.3 BV. This result does not contradict the earlier statements concerning the agreement in the rigidity spectra with those of the declining phase of cosmic rays because there is not sufficient helium data below 1.2 BV during this earlier period to justify a comparison in the 0.4 to 1.2 BV rigidity region. Also, although there is certainly the problem of not knowing the particle spectrum outside of the solar system, for the galactic spectra normally suggested, the splitting effect is at least qualitatively in agreement with the prediction of a modulation of the type proposed by Parker, since the protons have a higher velocity for a given rigidity than the helium nuclei and are therefore less suppressed.

C.E. Fichtel, D. E. Guss, G. R. Stevenson, and C. J. Waddington, "Cosmic Ray Hydrogen and Helium Nuclei during a Quiet Time in 1961," to be published in the Physical Review.

For a summary of this work, see W. R. Webber, Progress in Elementary Particle and Cosmic Ray Physics Vol. VI, (1962). See particularly fig. 31a.

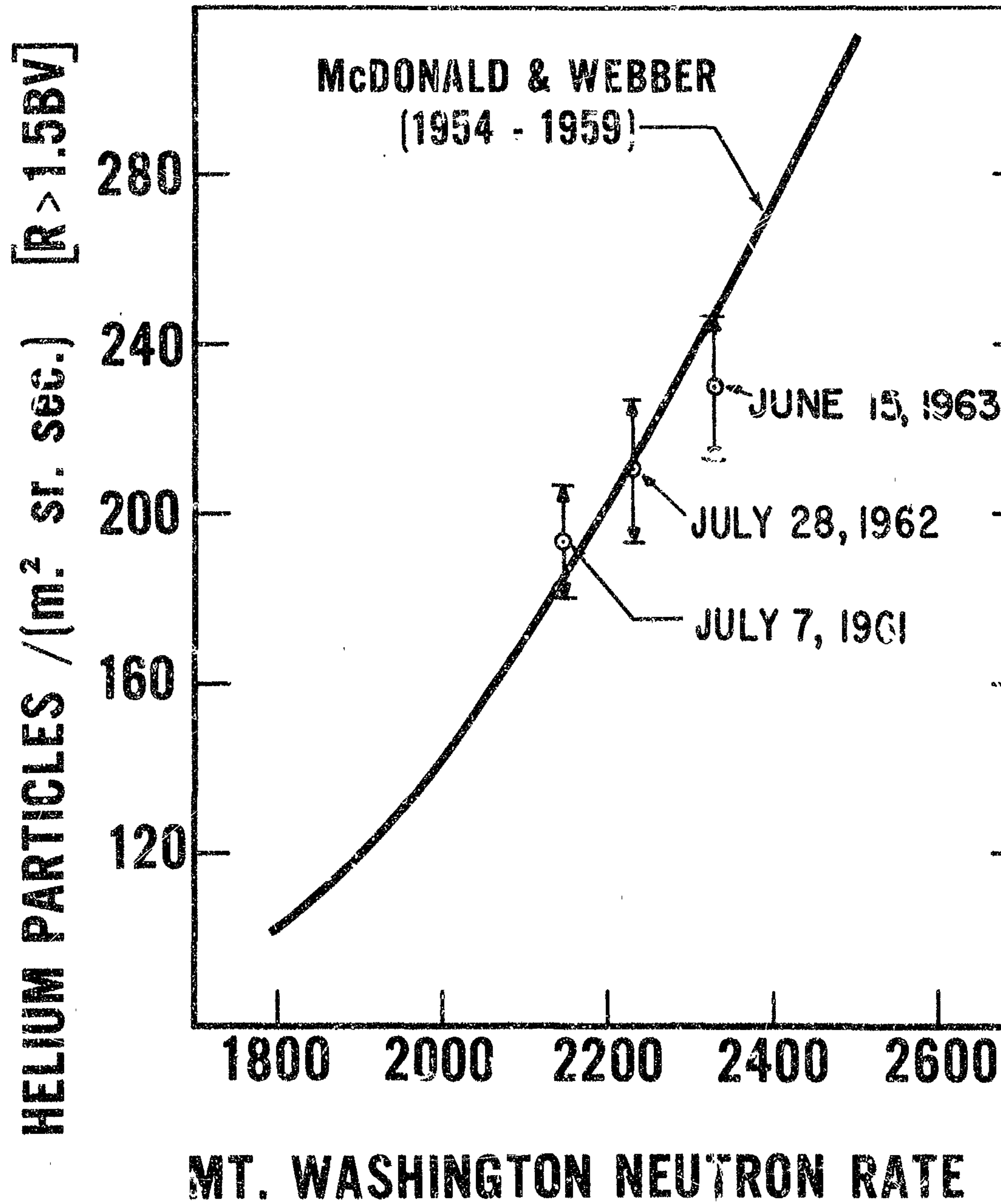
V.K. Balasubrahmanyan and F. B. McDonald, preceding paper, International Conference on Cosmic Rays, 1963.

Figure Captions

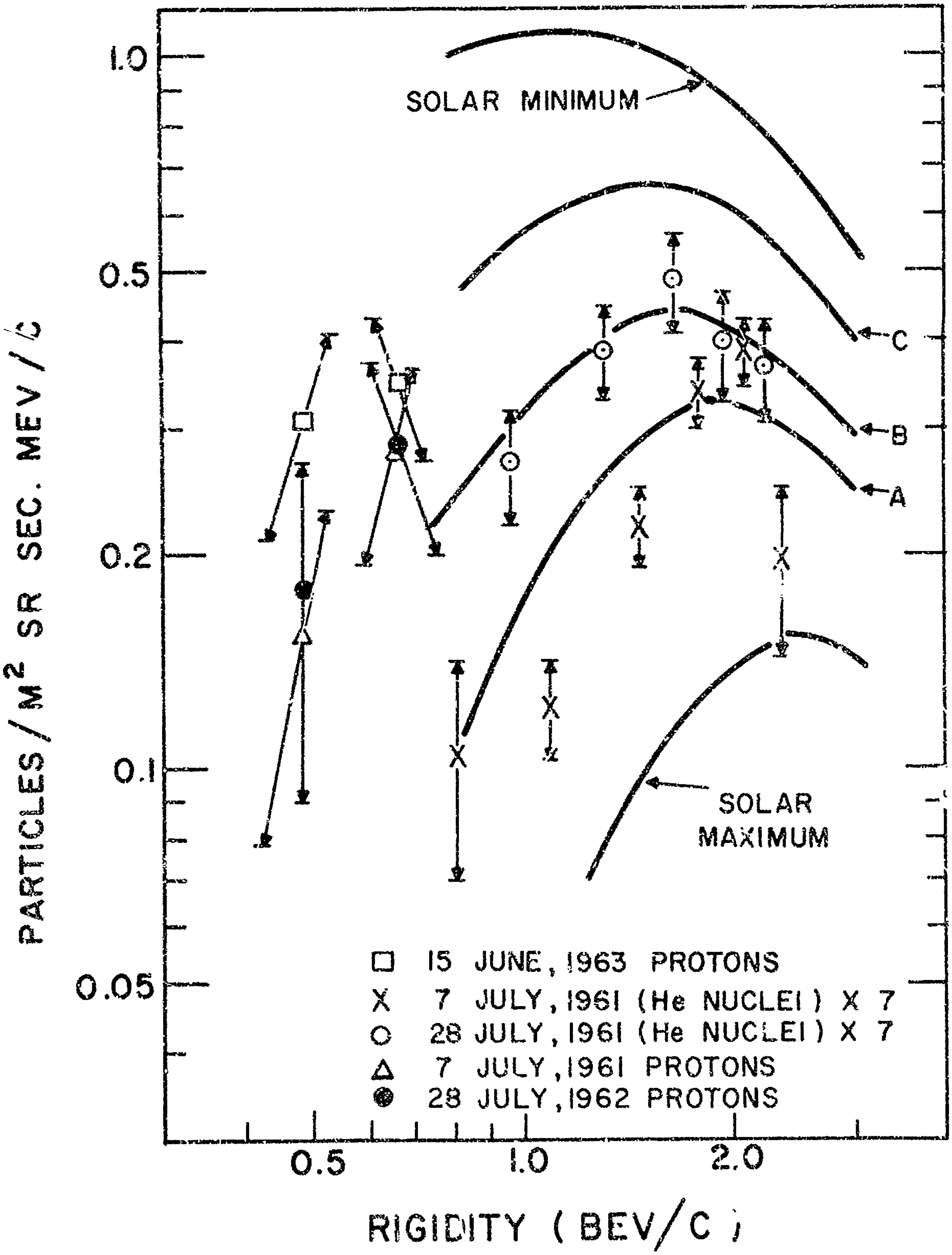
Figure 1: Integral Helium Particle Flux as a Function of the Mt. Washington Neutron Rate.

Figure 2: Differential Proton and Helium Fluxes as a Function of Ridigity. The solid curves are taken from figure 31a of Webber's review article and represent either the differential proton flux or the helium nuclei flux multiplied by seven for solar maximum. Curves A, B, and C correspond to times when the neutron monitor rates were the same as on July 7, 1961, July 28, 1962, and June 15, 1963 respectively.

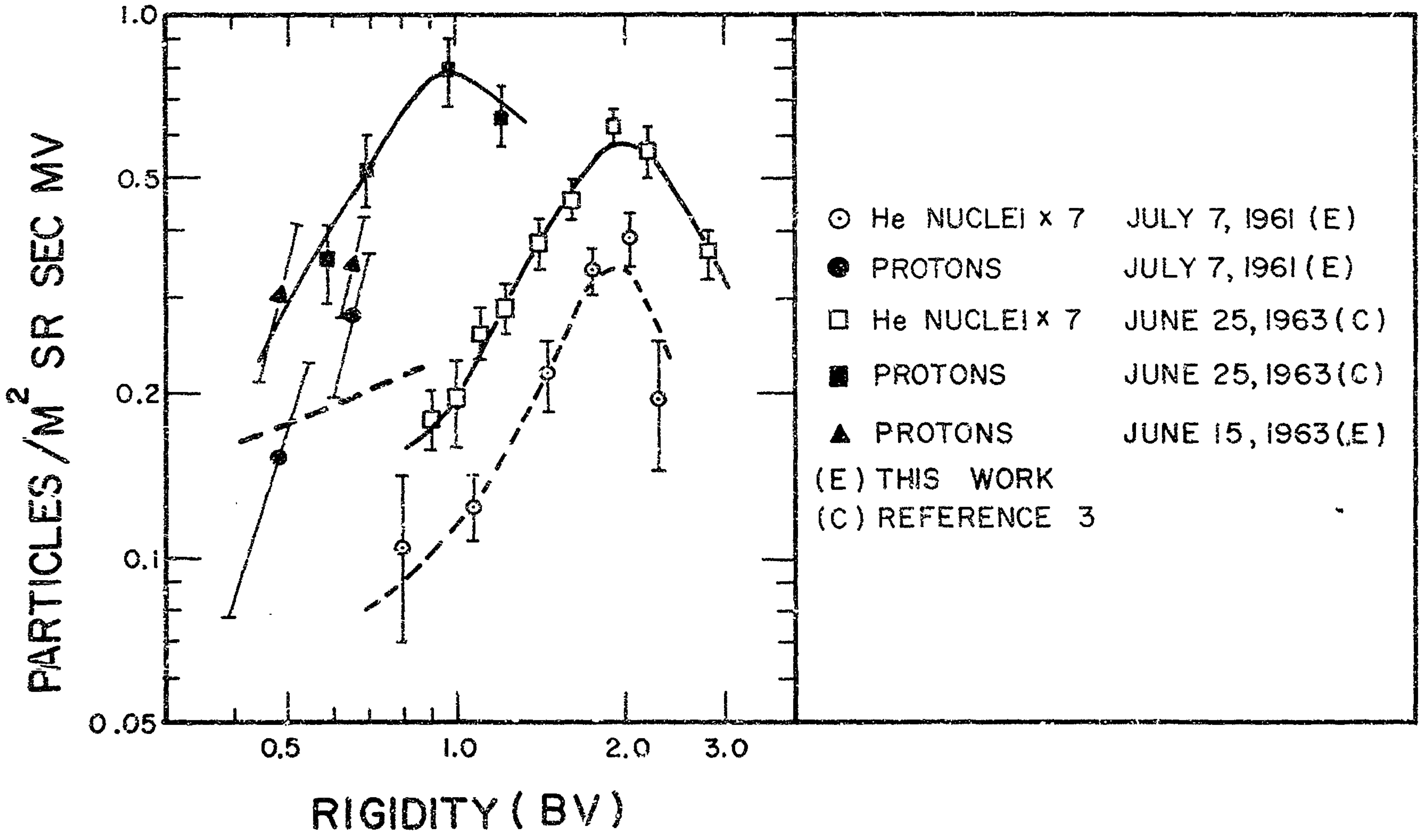
Figure 3: Differential Proton and Helium fluxes compared to those of Balasubrahmanyan and McDonald[3].



McDONALD & WEBBER
(1954 - 1959)
JUNE 15, 1963
JULY 28, 1962
JULY 7, 1961
HELIUM PARTICLES /(m.2 sr. sec.) [R > 1.5BV]
280
240
200
160
120
1800
2000
2200
2400
2600
MT. WASHINGTON NEUTRON RATE



SOLAR MINIMUM
SOLAR MAXIMUM
C
B
A
1.0
0.5
0.2
0.1
0.05
0.5
1.0
2.0
PARTICLES / M² SR SEC. MEV / C
RIGIDITY (BEV/C)
15 JUNE, 1963 PROTONS
7 JULY, 1961 (He NUCLEI) X 7
28 JULY, 1961 (He NUCLEI) X 7
7 JULY, 1961 PROTONS
28 JULY, 1962 PROTONS


PARTICLES /M² SR SEC MV
1.0
0.5
0.2
0.1
0.05
0.5
1.0
2.0
3.0
RIGIDITY (BV)
He NUCLEI x 7 JULY 7, 1961 (E)
PROTONS JULY 7, 1961 (E)
He NUCLEI x 7 JUNE 25, 1963 (C)
PROTONS JUNE 25, 1963 (C)
PROTONS JUNE 15, 1963 (E)
(E) THIS WORK
(C) REFERENCE 3

MEASUREMENT OF PRIMARY COSMIC RAY

CHARGE AND ENERGY SPECTRA DURING 1963

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Goddard Space Flight Center

Greenbelt, Maryland

ABSTRACT

The differential energy spectra of H and He nuclei in the interval 100 - 800 Mev/nuc, the integral H and He flux > 800 Mev/nuc and the cosmic ray charge spectra in the range Z = 1 - 8 have been measured using a three element telescope consisting of two thin scintillation counters and a Cerenkov Counter. The measurements were made from Fort Churchill, Canada on a Skyhook balloon flight during June, 1963. The ratio of Li + Be + B/C + N + 0 appears to be constant in the two regions 400 - 800 Mev/nuc and > 800 Mev/nuc. This ratio extrapolated to the top of the atmosphere is 0.28 ± .08. A marked difference is observed in the form of the low rigidity differential spectra of H and He. These measurements are compared with the results available from the last solar cycle.

Introduction

The objectives of the experiment reported here are two fold:

(a) To develop an improved detector system with adequate charge and energy resolution so that individual charges, their absolute intensities, energy spectra and time variation could be studied with the long range aim of using the detector in a satellite borne experiment.

Experimental Set-up

A schematic drawing of the detector system is shown in Fig. 1. The system is similar in principle to that reported by McDonald and Webber[1] except for

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some technical improvements to achieve better charge and energy resolution. For each particle traversing the telescope, the pulse height from all three detectors are recorded. For each detector there is a 512 channel pulse height analyzer and the data is recorded on a balloon borne tape recorder. The total weight of the complete system including batteries and pressure can is 65 lbs.

The results of a balloon flight on 24 June 1963 are reported here. During this flight the balloon remained for 12 hours at a ceiling altitude of 5 gms/cm^2. The equipment performed reliably through out the flight and the pre-flight and post-flight calibrations were in agreement with each other. The period during the flights was characterised by a quiet sun, with no abnormal activity.

Results

Fig. 2 shows the charge resolution obtained in the region Z = 2 - 8. In the region 350 Mev/nuc ($>$ 5 Cerenkov Pulse height) there is excellent resolution between all components. The L/M ratio at the observation level of 5 gm/cm^2 for the energy range 400-800 Mev/nucleon, = $.36 \pm .07$ where as for the energy $>$ 800 Mev/nucleon the ratio is $.36 \pm .09$. The ratio extrapolated to the top of the atmosphere using fragmentation parameters of Friedlander et al.[2] is $0.28 \pm .08$ in agreement with the results at Texas 41^{o}N.[3]

A summary of the results on the charge distribution obtained in this experiment is shown in Table 1. Also shown there, are results from previous measurements from other experiments.

Table 1

Comparison Of Charge Distributions Obtained At The Top Of The Atmosphere

Charge Distribution (Percent)

Charge	Balasubrahmanyan & McDonald	Waddington[3]	Aizu[4] et al	Tamai[5]	Fichtel[6]	O'Dell[7] et al
Li	8.8	3.9	8.8	10.0	7.4	5.3
Be	6.4	1.7	6.0	14.0	5.7	2.3
B	8.1	11.6	10.9	15.7	9.0	7.4
C	31.4	26.0	29.2	18.8	27.1	30.1
N	9.2	12.4	14.8	7.8	15.3	9.7
O	16.6	17.9	14.4	7.3	14.4	19.4
Z 10	19.5	23.9	21.7	20.5	21.7	23.5

Modulation

Fig. 3 shows the integral intensity of He nuclei, the me ium and heavy nuclei as a function of neutron count. For rigidity >1.5 BV the agreement between the curve obtained by Webber and McDonald during the last solar minimum, shows that at medium rigidities the sea level neutron count correlates well with the direct measurements. This gives a measure of confidence regarding the accuracy of the measurements.

Fig. 4 shows the differential rigidity spectra of protons and He nuclei. There are some interesting features which this figure reveals. First the differential intensity of Helium nuclei of rigidity > 2 BV appears to have recovered to the previous solar minimum period. On the low energy side, the previous measurement at International Falls, Minnesota is higher than both the proton and He curves of the present experiment. So, on the low rigidity side the recovery is still not complete.

Another interesting feature is the difference in rigidity spectra between the proton and He nuclei curves. The recovery for protons has been faster than for He nuclei for the same rigidity. In Fig. 5 the results of the counter measurements and that of Nuclear Emulsion measurements by Fichtel et al.[8] are shown. The good agreement between the results of these two entirely different experiments, particularly in the field of intensity measurements of low energy protons, where the secondary corrections etc. are applied on an entirely different and independent basis, gives one a measure of confidence in the interpretation of these results and their bearing on the modulation process.

Parker [9,10] has proposed a diffusion model, wherein the solar wind is responsible for the modulation. In this model, the modulation at a given rigidity is different for particles with different charge to mass ratios because of the velocity dependence of the diffusion mechanism. This model predicts that the differential spectra of the helium nuclei and protons should be different, with the He nuclei being suppressed more than protons. The observations reported here are at least in qualitative agreement with Parker's theory.

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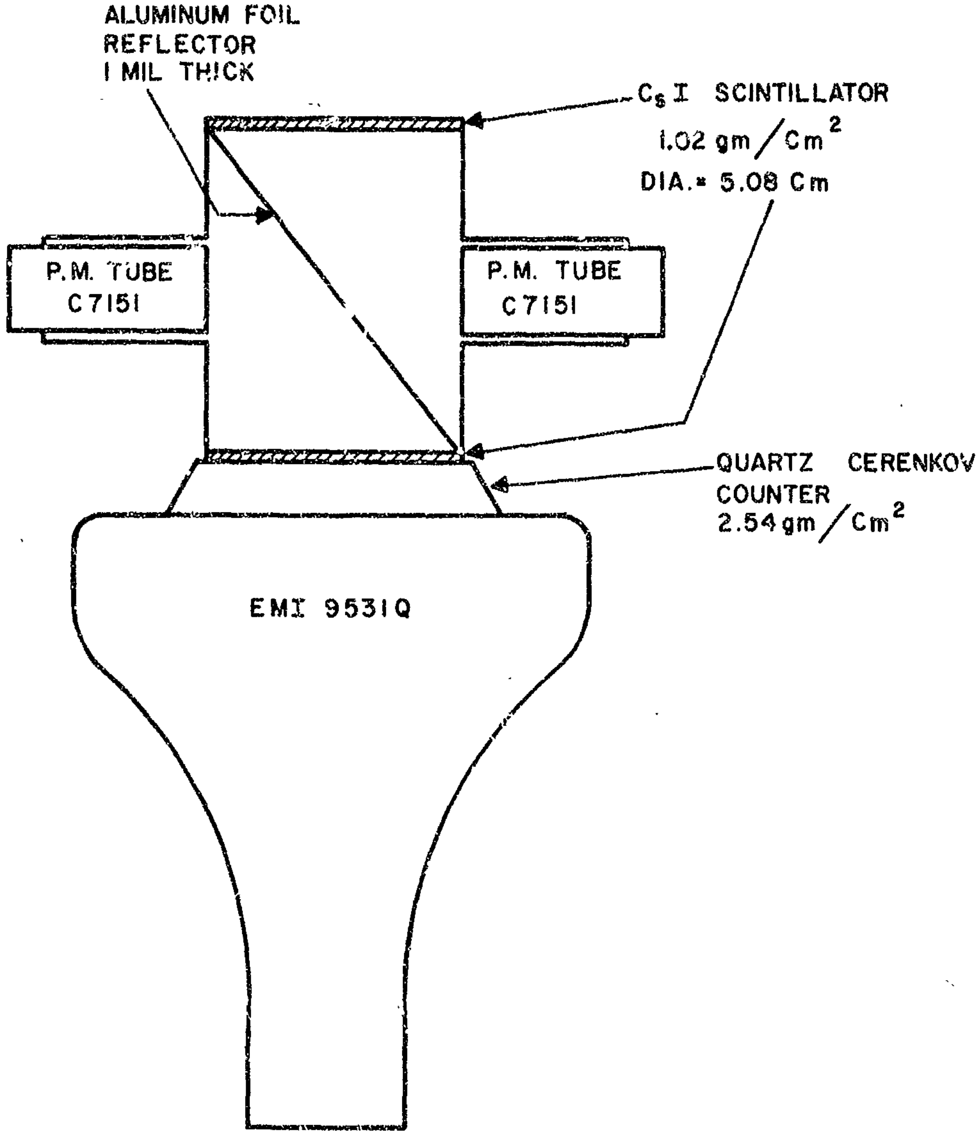
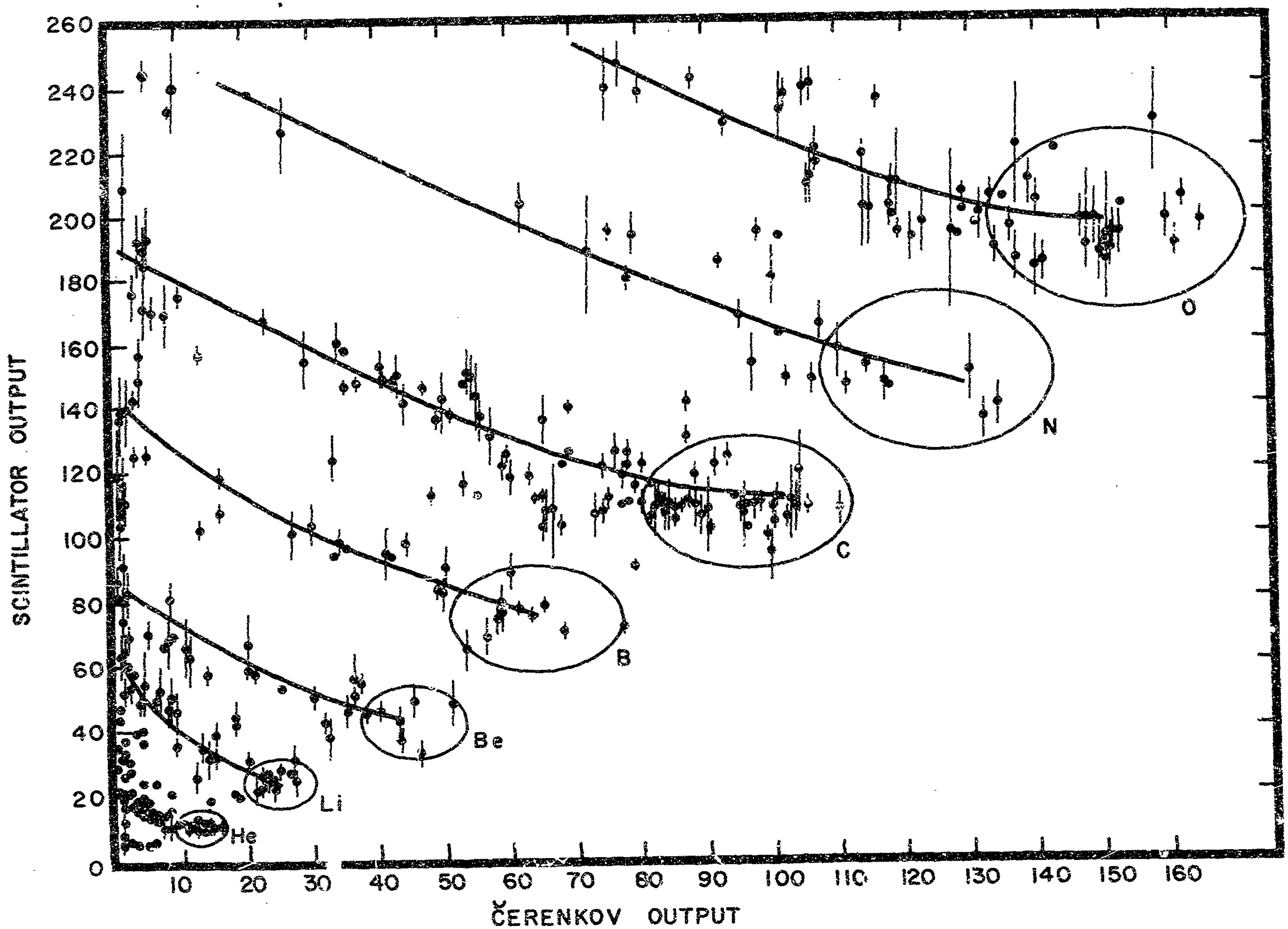
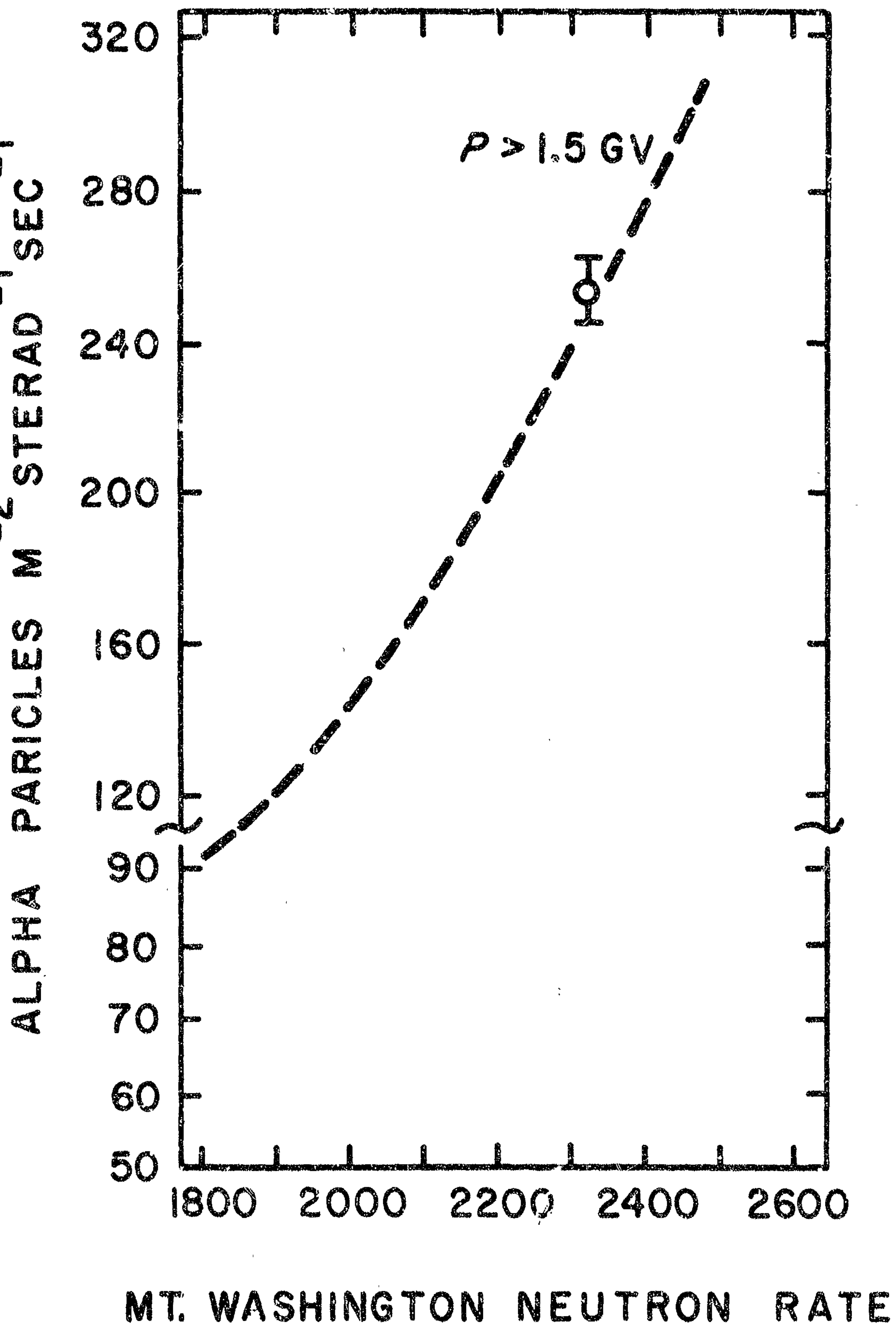


DOUBLE SCINTILLATOR—
CERENKOV COUNTER TELESCOPE

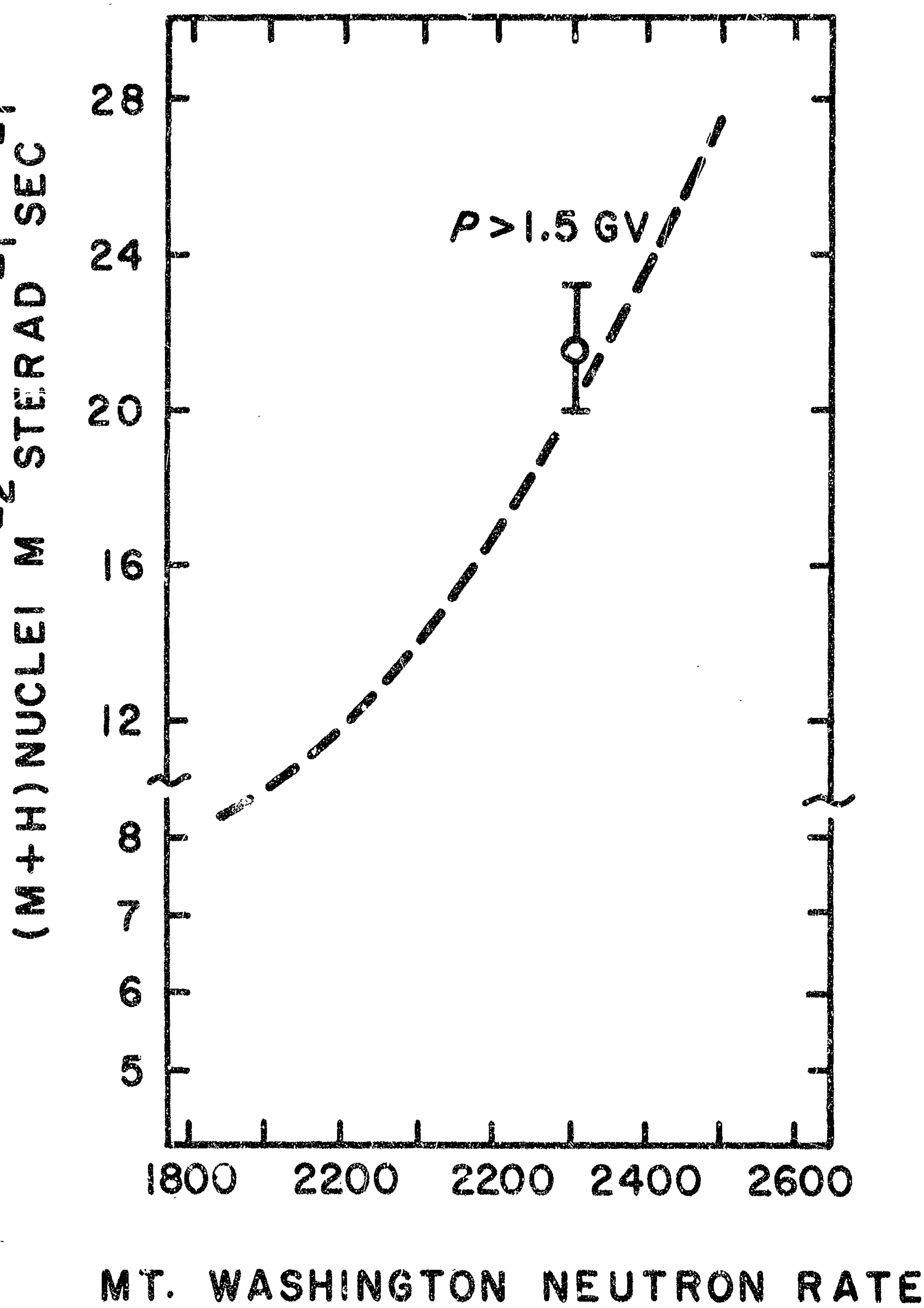
Fig. 1 -GEOMETRY



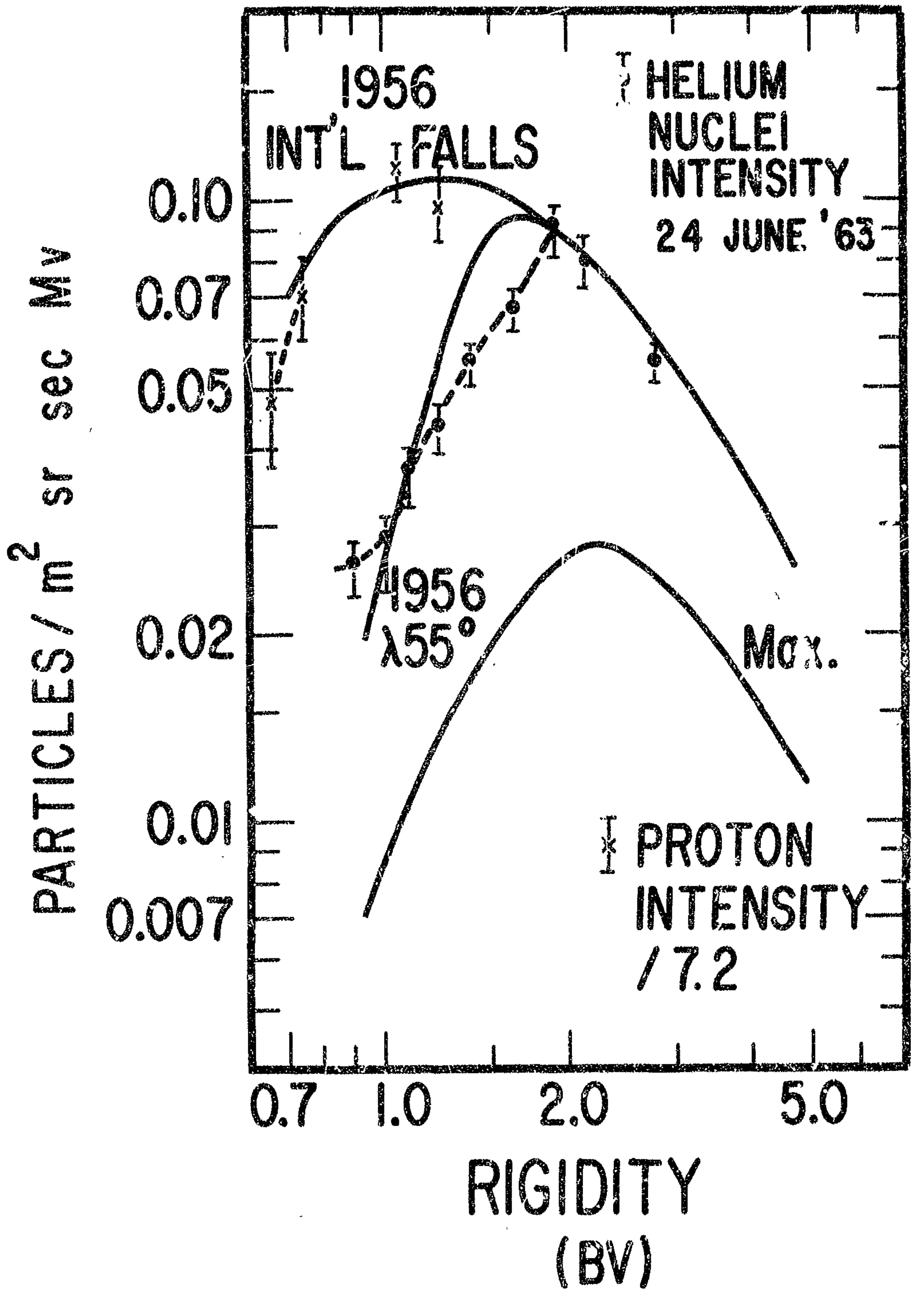
PLOT OF ČERENKOV OUTPUT vs IONIZATION LOSS IN TELESCOPE



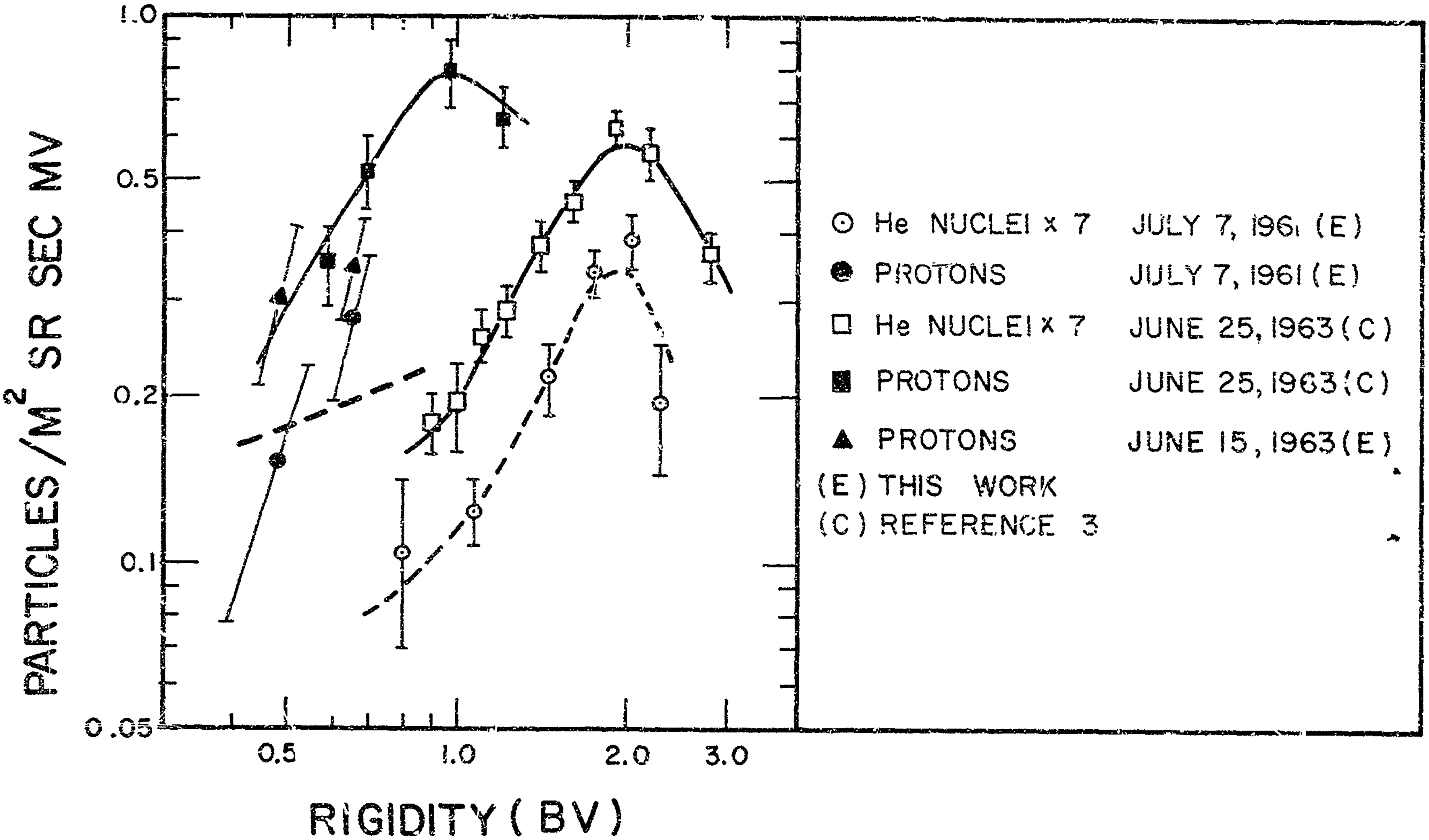
ALPHA PARICLES M^{-2} STERAD^{-1} SEC^{-1}
320
280
240
200
160
120
90
80
70
60
50
$P > 1.5$ GV
1800
2000
2200
2400
2600
MT. WASHINGTON NEUTRON RATE



(M+H) NUCLEI M^{-2} STERAD^{-1} SEC^{-1}
28
24
20
16
12
8
7
6
5
P>1.5 GV
1800
2200
2200
2400
2600
MT. WASHINGTON NEUTRON RATE



ALPHA AND PROTON RIGIDITY SPECTRA



PARTICLES /M² SR SEC MV
1.0
0.5
0.2
0.1
0.05
0.5
1.0
2.0
3.0
RIGIDITY (BV)
He NUCLEI x 7 JULY 7, 1961 (E)
PROTONS JULY 7, 1961 (E)
He NUCLEI x 7 JUNE 25, 1963 (C)
PROTONS JUNE 25, 1963 (C)
PROTONS JUNE 15, 1963 (E)
(E) THIS WORK
(C) REFERENCE 3

VELOCITY DEPENDENCE AND SOURCE SPECTRA OF SOLAR PROTON EVENTS[+]

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N65 10683

It has become clear from recent satellite measurements[1,2] that solar protons can be transported from the sun to the earth in three distinct ways in addition to the direct way sometimes observed with cosmic-ray monitors at sea level[3]. We wish to describe these four modes of propagation and then show how the velocity dependence of one of these modes makes it possible to determine the energy spectrum of the particles at the time of release from the sun.

We classify solar particle events consisting of radiation with energy above 1 Mev into four distinct classes. The distinction between the classes depends upon the way in which the particles are transported from the sun to the region of the earth. The first two classes consist of particles that arrive at the earth in a manner determined by particle velocity; the first class consists of predominantly higher-energy anisotropic particles that arrive after nearly a direct transit and the second class consists of those that arrive after a diffusive propagation; the third class consists of those that arrive in a manner determined by the motion of enhanced solar plasma; the fourth class consists of those that depend upon the rotation of the sun. Typical delays between the occurrence of a solar flare and the arrival at the earth of particles in these four classes are different. The delay of the first class event is close to the rectilinear transit time for highly relativistic particles and is therefore only a few minutes. The arrival-time delay of the second class depends upon the rate at which particles propagate through interplanetary space and so varies with energy up to a number of hours. The typical delay for particles in the third class is not a function of energy since particles of all energies arrive with the enhanced solar plasma responsible for Forbush decreases and geomagnetic storms; it is the transit time of solar plasma across one astronomical unit, that is, about two days. The fourth class event takes place near the time of central-meridian passage of a plage region responsible for a flare and solar particle events of the other classes during the previous solar rotation. This fourth class is closely associated with long-lived solar streams. The delay between the parent flare and the arrival of these particles is not a function of energy since particles of all energy arrive with the plasma stream. The delay depends upon the solar longitude of the parent flare and may therefore be as long as one solar rotation, or 27 days. Figure 1 shows the times of occurrence of events of the latter three classes seen by Explorers XII and XIV during parts of 1961 and 1962. Four sequences of events are evident. No events of the first class were seen with sea-level monitors during these time intervals. Figure 2 shows the variation in intensity of interplanetary protons of energy greater than 3 Mev during a sequence involving all the three classes of events seen. Superimposed on the intensity decay of the velocity-ordered event of 28 September is the plasma-associated event of 30 September, followed in turn after 27 event-free days by a recurrent event on

27 October.

We now confine our attention to several velocity-ordered events observed on Explorers XII and XIV. We show how it has been possible in these events to determine separately the influence of the propagation medium and the form of the energy spectrum of particles released from the sun, that is, the source spectrum. These deductions were made possible by the fact that differential energy measurements could be made outside the magnetosphere with the equipment carried by these satellites.

A striking velocity dependence was shown by the solar proton event of 28 September 1961. This is shown by Figures 3 and 4. Figure 3 shows intensity vs. time profiles for various differential energy components. The abscissa is in units of hours from the time of the flare. Figure 4 shows the behavior of the intensities of the same differential components of the event but this time plotted not as a function of time but as a function of distance travelled. The distance travelled is simply the product of particle velocity and time from the flare. The intensity curves of the various components have been vertically scaled to give the best fit to a common curve. The physical meaning of this normalization will be examined further below. We note from Figure 4 that all components lie very closely on a common curve. We may interpret Figure 4 as a measure of the probability that a particle should travel a given distance before reaching the earth from the sun. The fact that we have essentially a common curve shows that particles of all energies travelled a given path length with equal probability. This is true for all path lengths to the extent that the various components of Figure 4 lie on a common curve. The statistical distribution of path length travelled is clearly a property of the propagation medium of interplanetary space. We note that the distance travelled by most particles is an order of magnitude larger than one astronomical unit. This indicates that propagation involved an important degree of scattering. Further, the degree of scattering is not a function of energy over the range examined. This suggests that the mode of propagation is a diffusion-like process and that energy-dependent processes, such as drift across magnetic field lines, do not play a dominant role. In fact, the equation for simple diffusion fits the propagation curve of this particular event through its maximum. It does not fit, though, at the beginning where anisotropy is dominant and at the end where boundary conditions must be taken into account.

Some of the other solar proton events we have observed with Explorers XII and XIV show the same degree of good fit to common, velocity-compensated, intensity vs. distance curves, but a few contrast by not fitting at all. We believe that these exceptions do not weaken our argument for velocity dependence but strengthen it by illustrating that there are times when the properties of the propagation medium cannot, by this technique, be sorted from the source characteristics because, for example, the medium could be changing as the particles are propagating through it. In fact, some solar events may thereby be combinations of events of our first three categories. Although our observations indicate that solar proton intensities in some cases depend very closely upon the first power of velocity, a choice between velocity and rigidity dependence cannot be made from these data alone. There are indications from earlier emulsion measurements of solar proton and alpha intensities[4], however, that velocity dependence is preferable.

We discuss now the physical meaning of the scaling factors used to construct Figure 4. Let us consider the relative intensity of two components of the event. We have recorded the intensities not as a function of time but as a function of distance travelled and found that the ratio of intensities is essentially constant over a range from 2 astronomical units to more than 100 astronomical units. There is nothing to suggest that an extrapolation back to zero distance is invalid. The ratio of the intensities of two components at zero distance is, by definition, a measure of the shape of the source spectrum. Figure 5 shows the source spectrum obtained directly from the scaling factors used to produce Figure 4. The source spectra of two other events analyzed in a similar way are also shown. The ordinate of Figure 5 is arbitrarily chosen to be the maximum intensity reached at the earth. The differential intensities shown are proportional to the absolute differential intensities of protons produced at the sun and retain, therefore, the same spectral form, but the constant of proportionality depends on the geometry of propagation, which is unknown. (For example, since simple diffusion theory fits this propagation curve through maximum intensity, the numerical solution it gives for the source intensity is of the same spectral form, but that solution is for diffusion in an infinite, isotropic sphere, and is probably not a meaningful one.)

We note from Figure 5 that the source spectra are commonly very well represented by power laws in kinetic energy. This fact prompts us to put forward the argument, based purely on aesthetic grounds, that the amount of matter traversed by the solar protons after acceleration was less than the range of 1 Mev proton, that is, about 1 milligram cm^{-2}. It seems highly unlikely that an excess production of lower-energy protons would so exactly compensate their absorption in an amount of material greater than their range such as to produce so simple a form of source spectrum.

An interesting feature of these events is the existence of small-scale deviations from a common curve. Superimposed on the generally velocity-dependent intensity-time profiles are fluctuations which are nearly periodic with the same frequency and phase over the entire energy range studied. These fluctuations are evident in the velocity-ordered events discussed above, but are more striking in the 10 September 1961 event which showed no velocity dependence and was no doubt influenced by greater interplanetary disorder. Figure 6 shows plots of some sample intensities and indicates the periodic fluctuations. In this event the period is about 1.5 hours; in other events the period is slightly different. Since the transit-time dispersion over the energy range studied is significant, the fact that, in any given event, the fluctuations have the same period and are in phase at all energies shows that their origin is local. We suggest, therefore, that they reflect the magnetic field structure in local interplanetary space, but we as yet have no explanation for their periodicity.

+ Presented by T. L. Cline

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** Now at Physical Research Laboratory, Navrangpura, Ahmedabad, India

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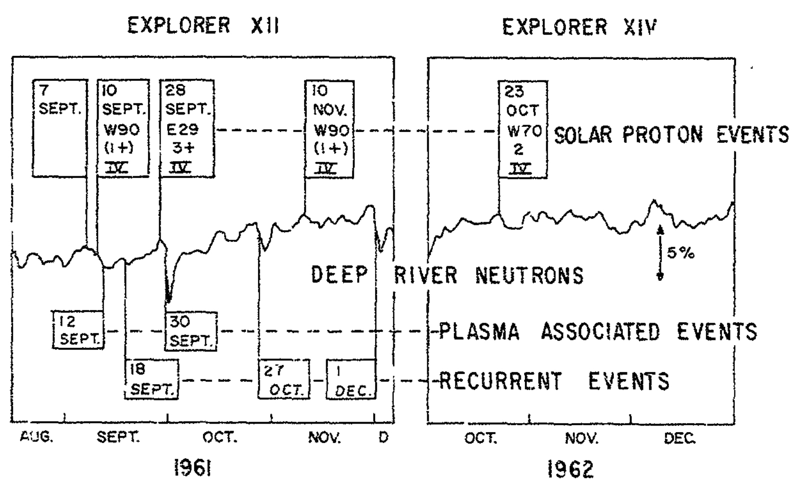

Figure 1

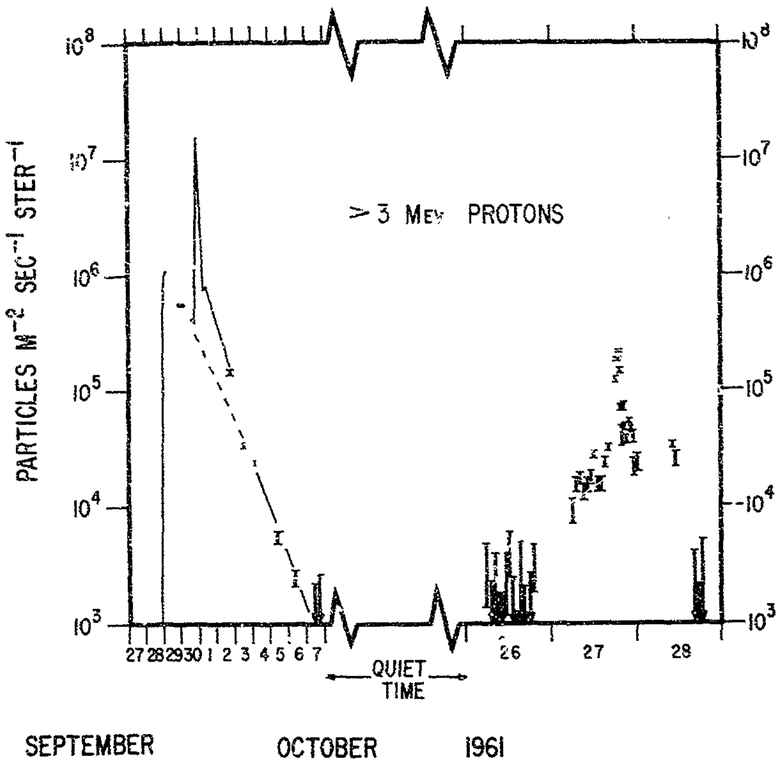

Figure 2

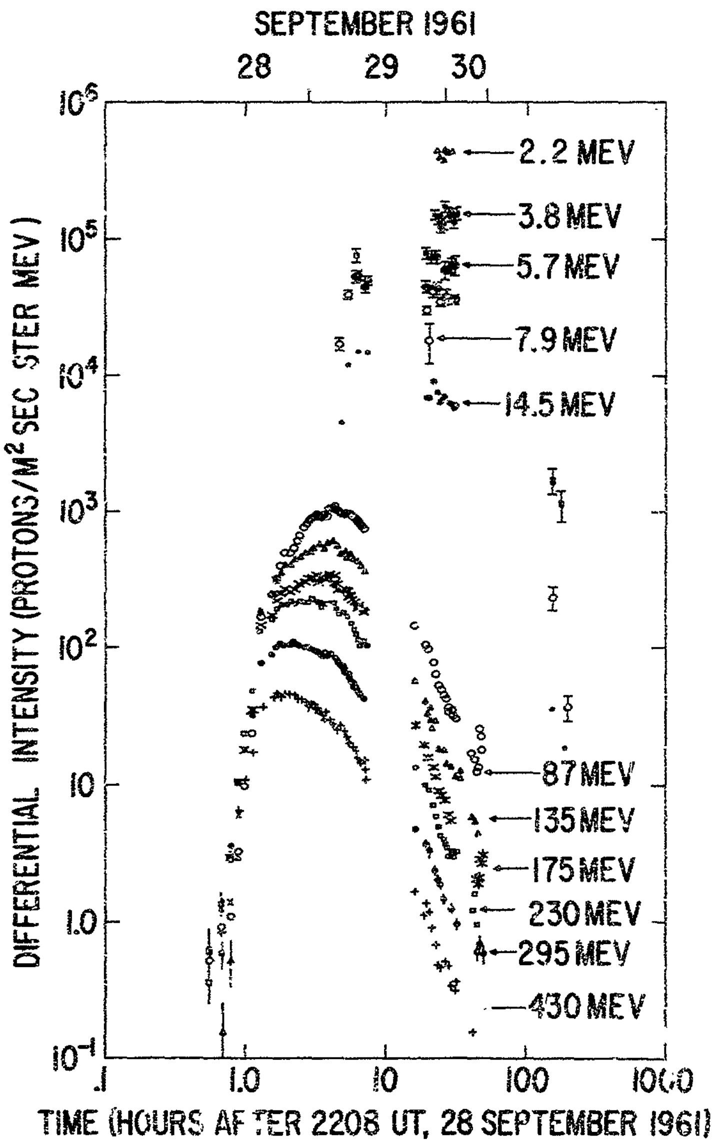

Figure 3

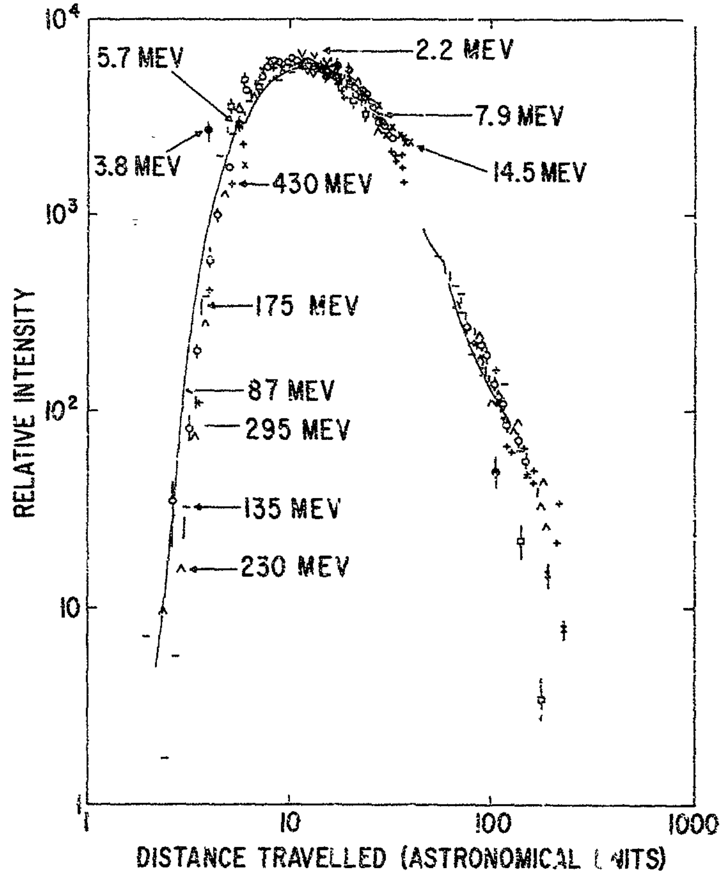

Figure 4

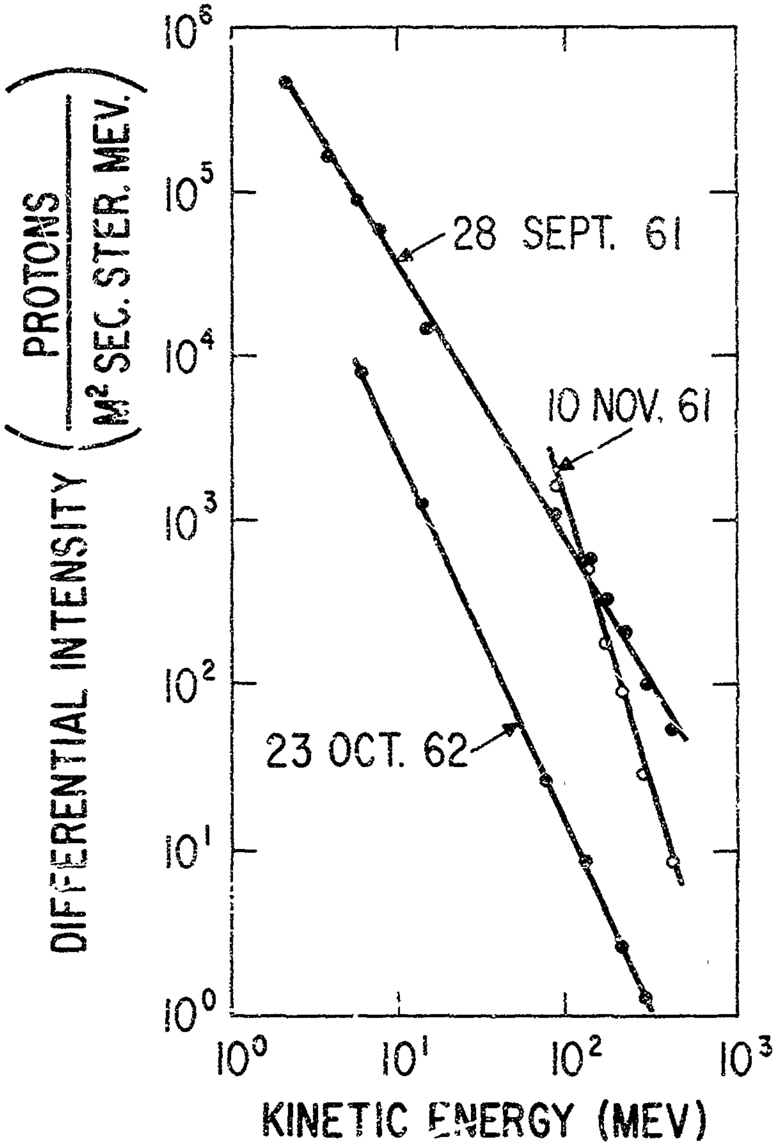

Figure 5

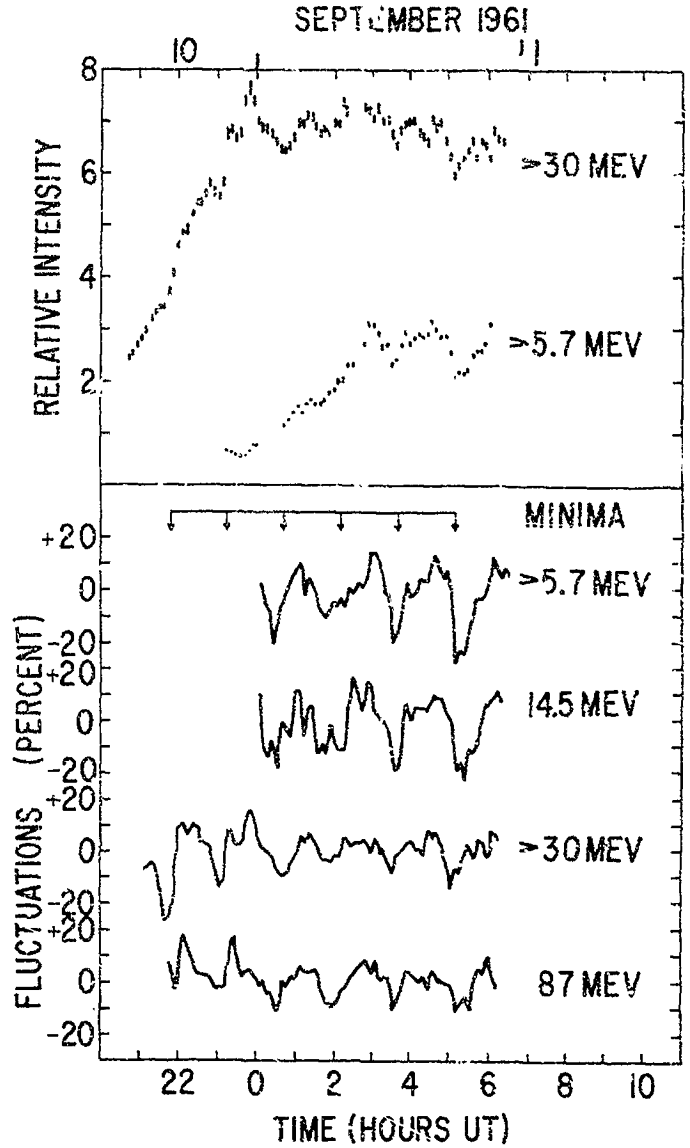

Figure 6